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Observations of Titan IIIC Transtage fragmentation debris

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ABSTRACT

The fragmentation of a Titan IIIC Transtage (1968-081) on 21 February 1992 is one of only two known break-ups in or near geosynchronous orbit. The original rocket body and 24 pieces of debris are currently being tracked by the U. S. Space Surveillance Network (SSN). The rocket body (SSN# 3432) and several of the original fragments (SSN# 25000, 25001, 30000, and 33511) were observed in survey mode during 2004-2010 using the 0.6-m Michigan Orbital DEbris Survey Telescope (MODEST) in Chile using a broad R filter. This paper presents a size distribution for all calibrated magnitude data acquired on MODEST. Size distribution plots are also shown using historical models for small fragmentation debris (down to 10 cm) thought to be associated with the Titan Transtage break-up.

In November 2010, visible broadband photometry (Johnson/Kron-Cousins BVRI) was acquired with the 0.9-m Small and Moderate Aperture Research Telescope System (SMARTS) at the Cerro Tololo Inter-American Observatory (CTIO) in Chile on several Titan fragments (SSN 25001, 33509, and 33510) and the parent rocket body (SSN 3432). Color index data are used to determine the fragment brightness distribution and how the data compares to spacecraft materials measured in the laboratory using similar photometric measurement techniques.

In order to better characterize the break-up fragments, spectral measurements were acquired on three Titan fragments (one fragment observed over two different time periods) using the 6.5-m Magellan telescopes at Las Campanas Observatory in Chile. The telescopic spectra of SSN 25000 (May 2012 and January 2013), SSN 38690, and SSN 38699 are compared with laboratory acquired spectra of materials (e.g., aluminum and various paints) to determine the surface material.

1. Introduction

On February 21, 1992 a possible propulsion explosion occurred in GEO, fragmenting the Titan IIIC Transtage (1968-081E; SSN 3432). The operator of the Ground-Based Electro-Optical Deep Space Surveillance System (GEODSS) sensor on Maui, Hawaii witnessed approximately 20 pieces in the breakup, but none were tracked at the time [1]. U. S. Space Surveillance Network (SSN) identified two pieces of the debris and assigned them to the catalog as SSN 25000 and 25001, earliest epoch of DOY 270 from 1997. In 2007 another fragmentation piece was added to the catalog: SSN 30000. Two years later, the following Titan debris pieces were added to the catalog: SSN 33509, 33510, 33511, 33512, and 33513. To date, 16 more pieces have been added to the catalog in association with 1968-081, specifically (SSN 38690 – SSN 38705). The outer-surface schematic for the Titan Transtage is shown in Fig. 1. The major surface properties consist of white silicon paint; the checkerboard pattern: 35% iridited aluminum and 65% aluminum silicone paint, and the forward barrel consist of white silicon paint [2]. Knowing materials *a priori* allows for better estimation on how reasonable the photometric measurements of the Transtage and the associated fragments are in regard to surface material determination.

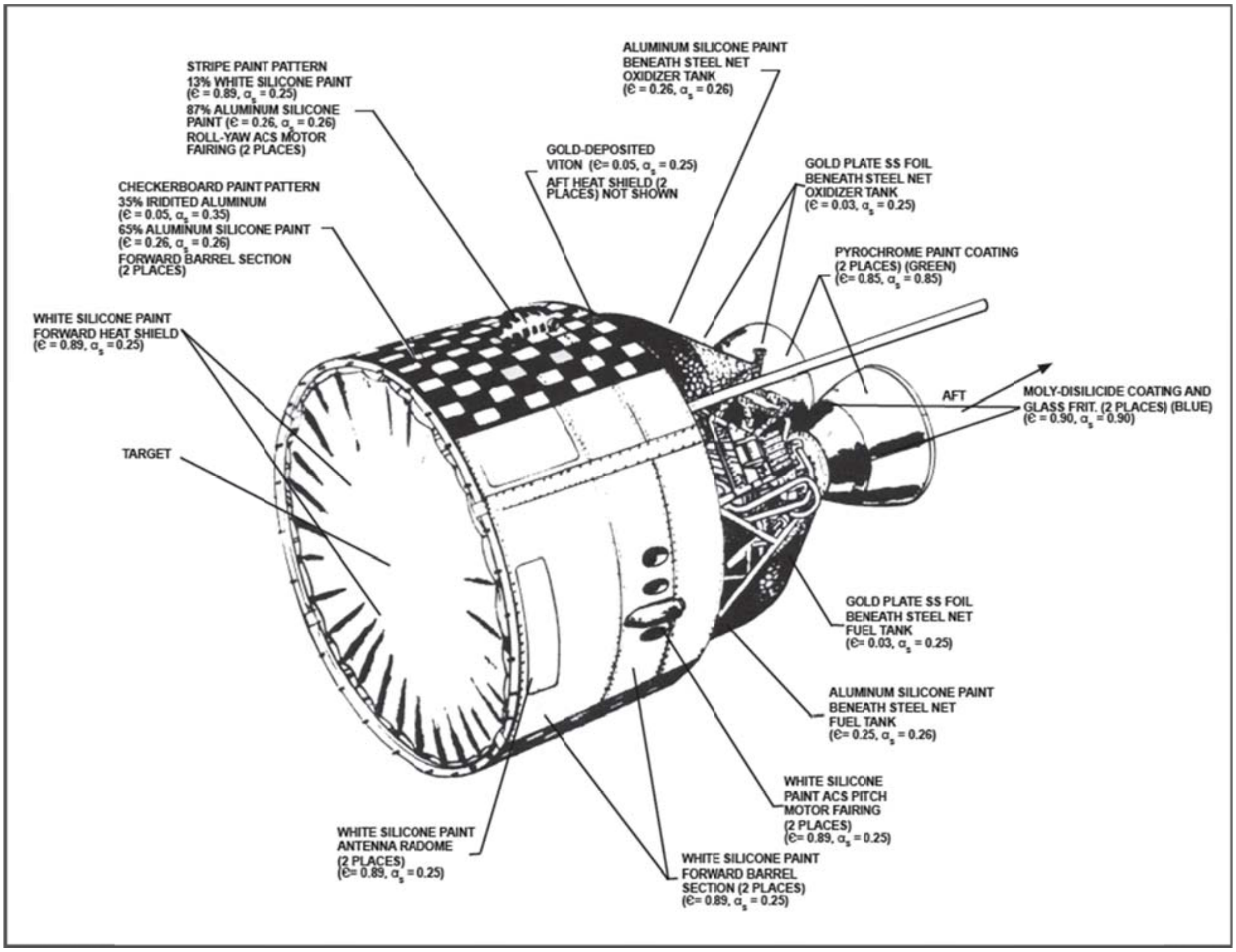

Fig. 1. Titan Transtage Schematic [2].

The earliest data acquired on Titan debris dates back to 2004 using the Michigan Orbital DEbris Survey Telescope (MODEST) located in Chile. MODEST is a 0.6-m Schmidt telescope stationed at the Cerro Tololo Inter-American Observatory (CTIO) complex. From 2001-2009, MODEST used a 2,048 x 2,048 pixel CCD with a field of view of 1.3° x 1.3° and 2.318 arc-second pixels. For typical survey modes, MODEST uses a broad-R filter (centered at 630 nm with a full width half maximum of 200 nm); given a 5-second exposure and a signal-to-noise ratio of 10, a limiting magnitude of 18 is acquired equivalent to a 20-cm diameter object in geosynchronous orbit.

2. Data Analysis

2.1 Size Distributions

MODEST generally operates in standard survey mode, time-delayed integration scanning at a particular RA and DEC field center to characterize the GEO or near GEO environment. Each observation has a unique frame number and associated RA, DEC, instrumental magnitude, epoch, observation date, and universal time stamp. The instrumental magnitude is transformed to a calibrated R magnitude by using a zeropoint based on Landolt standard star observations acquired the same night of observations and a mean airmass of 1.5. Over the time frame between 2002 and 2010, five different Titan objects passed through the field of view of MODEST during standard survey mode. The data are shown in Table 1, listed by date of observation in two forms: year and day of year (YYYYDOY) and month, day, year (MM-DD-YYYY), SSN number, calibrated Absolute Magnitude (ABSMAG) in broad R, Solar Phase Angle (α), equivalent spherical diameter (d) in meters, and radar cross section (RCS). The equivalent spherical diameter (d) is calculated assuming an albedo (A_g) of 0.175, Lambertian phase angle ($\Psi(\alpha)$), and range (R) of 36,000 km using the following equation:

$$d = \frac{2 \cdot R}{[\pi \cdot A_g \cdot \Psi(\alpha)]^{0.5}} \cdot 10^{\left[\frac{Mabs(v)+Msun(v)}{-5.0}\right]}$$

The asterisks in Table 1 indicate specialty runs (i.e., the 2007 data were aimed at observing in RA and DEC space near Titan break-up fragments; many uncorrelated targets (UCTs) were found but only the rocket body was correlated). The diameters inferred by three observations of the rocket body (3432) are within ~0.2 m of each other based on calibrated magnitudes and observed phase angles. One of the fragmentation pieces (25001) has a larger spread in size (~0.41 m) likely attributed to aspect angle/orientation of the object over the various observation periods. Optical size calculations suggest SSN 25000 (d = 2.204 m, 12.9 mag and α = 25.48 deg) is slightly larger (2-3x larger) than fragments 30000 and 33511 (d = 0.568 - 0.714, R = 15.3-15.8 mag and α ~18-19 deg phase angle) as one would expect given the differences in magnitude of these objects.

Table 1. Observed Titan targets given calibrated broad R magnitudes and equivalent size diameters.

Date		SSN	ABSMAG	α	d (m)
2004029	01-29-2004	3432	12.3	17.98	2.840
2007049*	02-18-2007	3432	12.37	13.86	2.725
2007050*	02-19-2007	3432	12.22	13.07	2.915
2008162	06-10-2008	25000	12.9	25.48	2.204
2008068	03-08-2008	25001	15.0	29.53	0.851
2007081	03-22-2007	25001	15.9	28.60	0.560
2006297	10-24-2006	25001	16.4	23.87	0.437
2009295	10-22-2009	30000	15.3	18.37	0.714
2009295	10-22-2009	33511	15.8	18.75	0.568

In 2007 an optical search was performed with MODEST in the phase space where Titan debris were expected to be for six consecutive nights based on predicted orbits from NASA's orbital debris evolutionary model LEGEND (LEO-to-GEO Environment Debris) [3]. Of the observed targets, 7 of the 15 targets (uncorrelated) had orbital motion consistent with the modeled Titan fragments. At the time of the observations in 2007, only SSN 3432, 25000, and 25001 were cataloged. In an effort to better understand the size and cumulative number of fragments associated with the Titan break-up, an updated figure is presented based on the new SSN numbers that have been added to the catalog since 2007. Fig. 2 shows these 25 pieces of cataloged Titan debris "Cataloged Titan" as well as LEGEND-generated fragments that have potential to be associated with the Titan break-up divided into two categories: >30 cm and >10 cm as a function of inclination (INC) and right ascension of ascending noce (RAAN). Using MODEST solely for detection of optically faint debris is limited to 18th magnitude detections (corresponding to a 20-cm size limit with a 0.175 albedo at 36,000 km, assuming it follows a diffuse Lambertian phase function). In an effort to detect fainter GEO objects (R = 20, ~10 cm diameter), campaigns employing the 6.5-m Magellan Telescopes at Las Campanas Observatory in Chile began in 2011. With nearly 120x greater light collecting area, the Magellan telescopes allow for fainter debris detection as well as access to spectroscopic instrumentation. Spectral data on three of the Titan fragments will be discussed in Section 2.3 Spectroscopic Results.

A paper was presented in 2013 summarizing how GEO tracklets are used to associate fragments with spacecraft breakup events such as the Titan breakup [4]. This paper presents an alternative method for associating fragmentation debris with the Titan break-up by use of a track-before-detect algorithm designed to stack images to increase the signal-to-noise ratio (SNR) and the k-NN algorithm which uses the object's predicted motion to statistically assess whether the object's motion is likely to be associated with the break-up of interest. Using the k-NN algorithm on 50 of 96 observed tracklets of uncorrelated targets, the results were found to show association between the uncorrelated targets and the Titan break-up [4]. Although this method shows good correlation in associating UCTs with the Titan break-up, the computational requirements are very high.

Based on both the LEGEND-generated population and the results using the k-NN algorithm, a larger population of smaller fragmentation debris associated with the Titan Transtage break-up can be assumed. The following discussion presents surface material characteristics of the observed Titan debris in comparison to laboratory photometry and spectroscopy data.

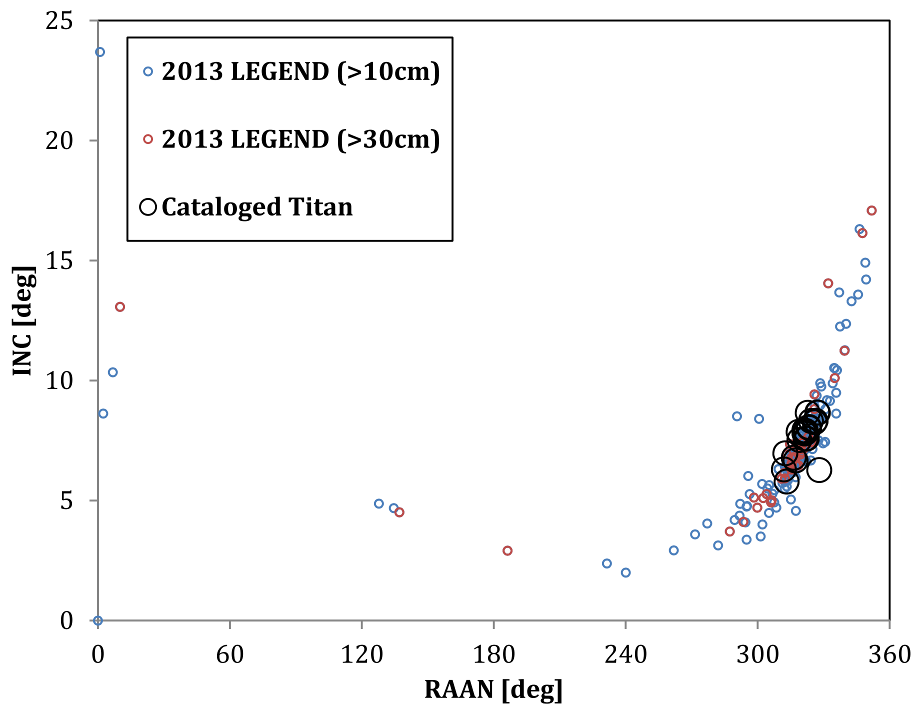

Fig. 2. Titan cataloged objects (shown with black circles) and LEGEND-generated fragments that are potentially associated with the Titan break-up, categorized into two size regimes: >30 cm (blue circles) and >10 cm (red circles). The objects >30 cm should be detectable using MODEST.

2.2 Photometric Results

Filter photometric data were collected on the Titan debris using the 0.9-m Small and Moderate Aperture Research Telescope System (SMARTS) at the CTIO in Chile. The CTIO 0.9-m telescope magnitudes and colors are derived from a series of sequential exposures (5 or 10 seconds) using the Johnson/Kron-Cousins R, B, I, V, and R filters. Typically, there are five exposures in each filter with the B filter having twice the exposure time since the SNR is generally lower in the B band. These images are measured with IRAF scripts to produce a sky subtracted magnitude in a fixed measurement aperture. The photometric error in each measurement is used as a weight in the calculation of the average magnitude (in intensity space) for a particular filter. Frames containing star trails, cosmic rays, or CCD defects within the measurement aperture are rejected from the average magnitudes. Photometric coefficients (zero point, extinction, and color term) have been determined from Landolt standard stars for each night. These coefficients are applied to the instrumental target magnitudes to produce calibrated magnitudes in each filter. The calibration errors for these magnitudes are propagated from the instrumental photometric errors and the calibration coefficient errors by standard root mean square methods.

Calibrated R magnitude data and color index data with respective photometric 1-sigma errors are shown for several Titan fragments in Table 2. The average solar phase angle (Avg. α) is determined from the start and end times of the filter sequence. The average calibrated uncertainty in R magnitude was ~ 0.037 mag with the maximum ~0.075 mag.

The color data shown for SSN 25001 on November 10, 2010 varies from the previous data entries likely due to very faint star trail contamination within the target aperture that could not be removed during post-processing, although the R mag and corresponding error is consistent with previous entries. Due to the possibility of contamination from faint unresolved stars in the crowded starfield background, a smaller aperture (3 pixels vs. 8 pixels used for all photometric reductions in Table 2) was used to minimize the effects of the sky background. The comparison values are shown in Table 3. A sample image of the processed data for November 10, 2010 is shown in Fig. 3, showing possible uncertainties in photometric data due to *faint* star trail contamination. Although, the colors could be true variations attributed to different materials visible as a function of aspect angle. Another possibly could be attributed to red stars trailing in the background, which would affect the I measurements the most, as shown in Table 3. The

R-I values have the largest difference using the 8 pixel aperture. The solar phase angle (SPA) is also 30°-35° larger than the original data points, which corresponds to an ~0.5 delta mag difference, assuming a Lambertian surface. The R mag difference is <0.3 mag over a phase angle spread of 37°, suggesting the material is not Lambertian, a long-held assumption that may not best fit orbital debris data. Reference [5] suggests that there are multiple hybrid-phase functions that would better fit the orbital debris model, but more research is needed to confirm this. The color data for these specific dates is being investigated.

Table 2. Observed Titan targets with calibrated R magnitudes and color indices in Johnson/Kron-Cousins B,V,R,I with associated 1 sigma uncertainties. Yellow = possible star trail contamination.

SSN	Date		R	R (err)	B-R	B-R (err)	B-V	B-V (err)	R-I	R-I (err)	Avg. α
3432	2010.309	11-05-2010	13.233	0.005	1.675	0.012	0.961	0.014	0.721	0.008	20.59
3432	2010.314	11-10-2010	13.36	0.005	1.72	0.013	0.99	0.014	0.7	0.008	30.24
3432	2010.314	11-10-2010	13.411	0.005	1.71	0.013	0.95	0.014	0.66	0.008	34.90
25001	2010.309	11-05-2010	16.916	0.070	1.386	0.158	1.053	0.164	0.337	0.147	25.98
25001	2010.309	11-05-2010	17.002	0.074	1.235	0.148	0.910	0.154	0.295	0.167	30.56
25001	2010.314	11-10-2010	17.276	0.042	1.280	0.094	0.786	0.107	0.387	0.086	58.33
25001	2010.314	11-10-2010	17.228	0.043	1.097	0.078	0.675	0.084	0.361	0.076	62.88
33509	2010.309	11-05-2010	13.201	0.006							19.94
33509	2010.309	11-05-2010	12.986	0.005	1.247	0.008	0.811	0.009	0.243	0.008	13.72
33509	2010.313	11-09-2010	13.445	0.006	1.141	0.010	0.603	0.011	0.378	0.010	47.99
33509	2010.313	11-09-2010	13.775	0.007	1.140	0.013	0.656	0.014	0.341	0.012	53.33
33510	2010.309	11-05-2010	16.376	0.051	1.107	0.096	0.788	0.099	0.513	0.095	23.54
33510	2010.313	11-09-2010	16.313	0.041	0.859	0.067	0.524	0.072	0.392	0.083	14.35
33510	2010.313	11-09-2010	16.249	0.039	0.909	0.067	0.538	0.072	0.376	0.080	18.11
33510	2012.108	04-17-2012	16.126	0.041	1.028	0.079	0.712	0.084	0.482	0.073	22.24
33510	2012.108	04-17-2012	16.176	0.044							44.12
33510	2012.110	04-19-2012	16.434	0.061	0.730	0.096	0.639	0.093	0.753	0.091	6.37
33510	2012.110	04-19-2012	16.459	0.047	0.655	0.095	0.534	0.103	0.824	0.081	14.12

Table 3. Photometry comparison values using different apertures for a crowded star field.

Aperture size (pixels)	SSN	Date		R	R (err)	B-R	B-R (err)	B-V	B-V (err)	R-I	R-I (err)	Avg. α
3	25001	2010.314	11-10-2010	17.276	0.042	1.280	0.094	0.786	0.107	0.387	0.086	58.33
8	25001	2010.314	11-10-2010	17.149	0.075	1.13	0.171	0.65	0.200	-0.04	0.261	58.33
3	25001	2010.314	11-10-2010	17.228	0.043	1.097	0.078	0.675	0.084	0.361	0.076	62.88
8	25001	2010.314	11-10-2010	17.142	0.075	0.9	0.149	0.5	0.166	0.65	0.154	62.88

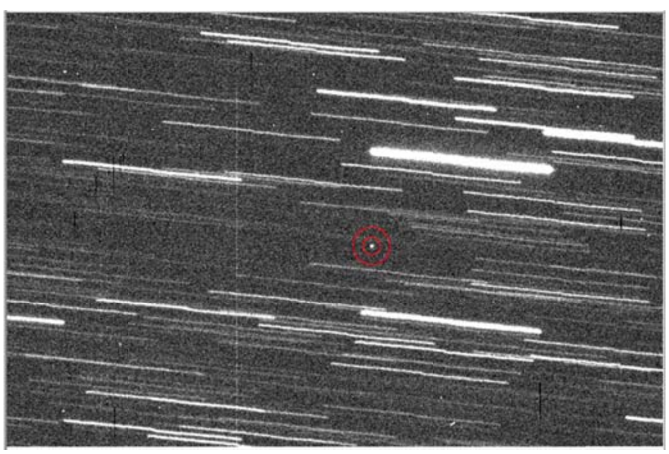

Figure 3. Sample image from DOY 314 in 2010 indicating star trail contamination. The inner circle, shown in red, corresponds to the inner sky annulus (9 pixels). The object's aperture (8 pixels) and the inner sky annulus are indistinguishable in the image. The outer circle, also red, illustrates the outer edge of the sky background annulus (19 pixels).

Fig. 4 shows the B-R and B-V color index data for several spacecraft materials measured in the Optical Measurement Center at NASA Johnson Space Center. The materials analyzed in the laboratory are not exposed to the environment, and thus do not experience space weathering (e.g., white paint tends to brown over time and multi-layered insulation [MLI] will redden in space). Incorporating the space weathering effects on spacecraft materials for laboratory analysis is an on-going effort. The laboratory data were taken using Johnson/Bessell B, V, R, and I filters and corrected to match solar values. All laboratory data were taken using a SPA ~ 6°. Future research will incorporate larger phase angles with better resolution. The spacecraft materials shown are (in order of top to bottom): intact MLI, copper space-facing MLI, aluminized space-facing MLI, copper spacecraft-facing MLI, aluminized spacecraft-facing MLI, Kyushu University post-impact MLI, Jet Propulsion Laboratory spacecraft solar panel, Spectrolab® UTL solar cell, Kyushu University post-impact fragmented solar cell, European Space Center Operations (ESOC) test fragment-aluminum alloy, glass-fiber reinforced plastic (GFRP), carbon-fiber reinforced plastic (CFRP), Satellite Orbital Debris Characterization Impact Test (SOCIT) potting-nugget, SOCIT fragmented circuit board resulting from impact testing, SOCIT aluminum flake resulting from impact testing, and SOCIT potted electronics resulting from impact testing. Details of the materials and the accompanying tests can be found in [6].

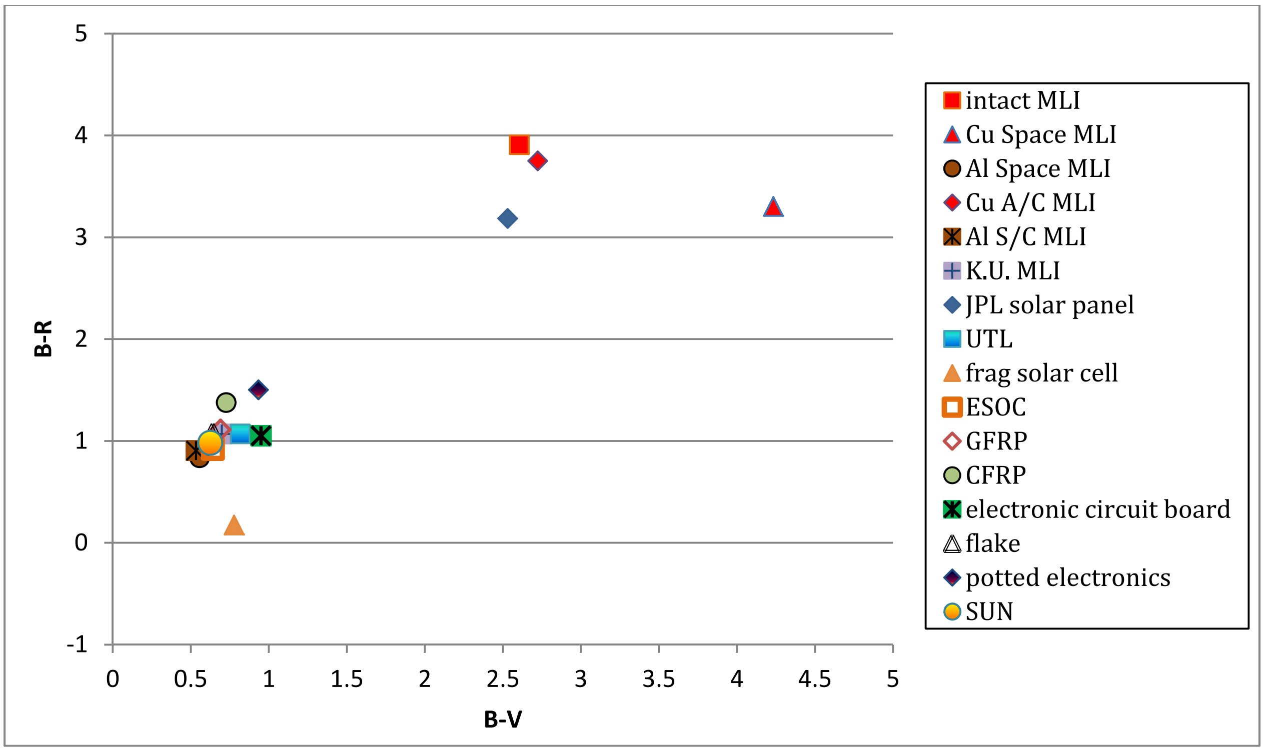

Fig. 4. Photometric B-R vs. B-V color indices for 14 laboratory fragments/materials.

Fig. 5 shows a comparison of the telescopic color indices with laboratory data shown in Fig. 4, but the plot axes have been rescaled to focus on the materials in close proximity to telescope data. Based on the laboratory data available, the higher color index values of the Titan Transtage (SSN 3432) indicate the fragment is a composite (combination of multiple materials), although the current state/presence of materials left on the Transtage is unknown. The composite "potted electronics" used in the laboratory was composed of electrical potting (white in the laboratory sample) and various electrical components (i.e., wires, resistors, etc.). Assuming the blue and green coatings around the Transtage liquid engines are still intact and the majority of the Transtage is painted with white silicone that may have browned over time, these effects would contribute to the higher B-V value. The presence of the gold deposited Viton on the heat shield and gold plate foil beneath the steel net agrees with higher B-R and R-I values (as listed in Table 2) than that of the other fragments.

Excluding the two data points for SSN 25001 associated with star trail contamination, the fragments show material properties within the color indices of the potted electronics and the electronic circuit board. Both of these materials are possible candidates given the electronics found in the guidance truss [2]. SSN 33509 is redder than solar colors,

based on the B-R, but the small spread in B-V between the three points suggests aspect angle dependence. The highest data point for SSN 33509 (B-R = 1.247 and B-V = 0.811) was taken at the smallest phase angle (13°) where specular reflections dominate the signal flux. The other two points were closer to phase angles of 50°, and within the region of aluminum ("flake") and GFRP. Since GFRP is translucent and thus not likely to create a specular component, it is plausible that the material is aluminum based, which can create specular flashes. Secondly, GFRP is not a likely candidate material associated with the 1968 Transtage. The last telescopic target, SSN 33510, had a much larger spread in magnitudes and associated phase angles than any other observed target. UTL solar cell and GFRP can be ruled out based on known materials associated with the 1968 Transtage. The other data points for SSN 33510 are close to the ESOC aluminum alloy and aluminum flake, both near solar colors. The variations in the magnitude spread would be indicative of an object composed of multiple materials in which different materials were illuminated at various observation periods. For example, an aluminum fragment that was painted blue or green on one side and raw aluminum on the other would show a color index spread similar to 33510. A fragment of this characteristic would likely be found on the aft of the main engine bells.

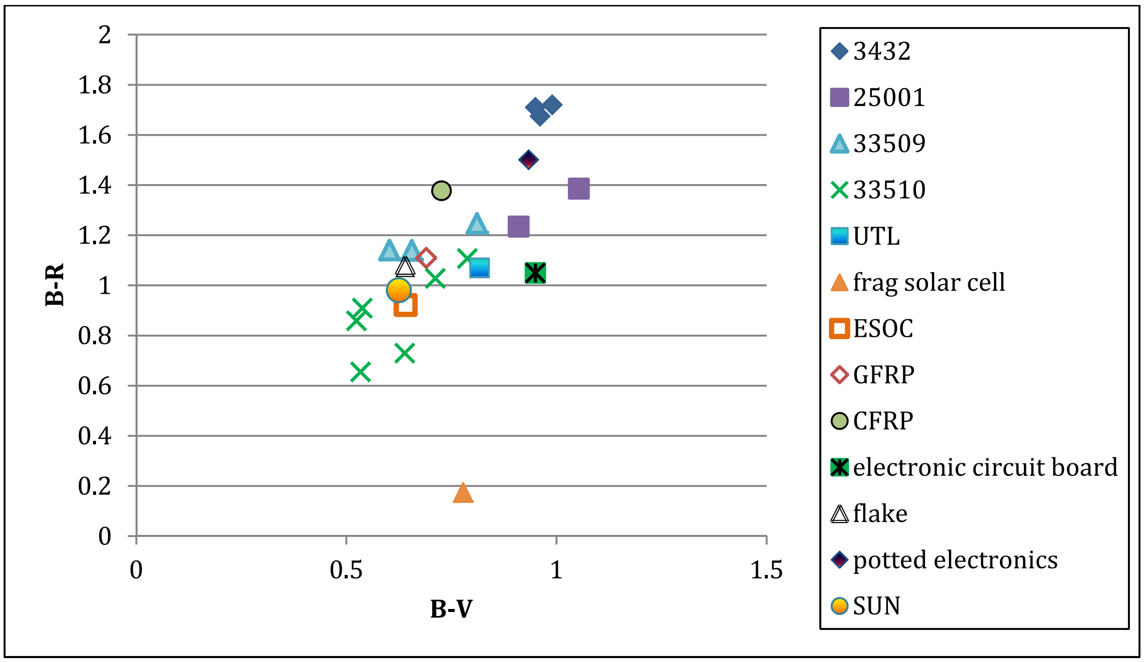

Fig. 5. B-R vs. B-V telescopic data in comparison to laboratory data

2.3 Spectroscopic Results

In May 2012 and January 2013, spectral measurements were collected on several GEO targets using the imaging spectrographs on the 6.5-m Clay Magellan Telescopes. The data were acquired using the Low Dispersion Survey Spectrograph (Version 3) and covers the visible range between 4000-8000 Angstroms (Å). The data have been normalized to one at 7500 using an average value from 7500-8000 Å. Details of the observations/instrumentation are presented in [7]. Fig. 6 shows spectra data acquired from May 2012 on SSN 25000 and three sets of data from January 2013 on SSN 25000, SSN 38690, and SSN 38699. All data were normalized to 1 in the 7500-8000 Angstrom region and smoothed using an 11 point moving average (~20 Angstrom resolution). All data from January 2013 have been divided by the same solar analog star. The spectral data on SSN 25000 appear to be consistent over the ~8 month time span; both exhibit a slight slope increase with increasing wavelengths. The other two Titan fragments (SSN 38690 and 38699) are bluer than the former Titan fragment, shown by the higher ratio spectra in the blue/green region (<6000 Å). The characteristics of the spectra for SSN 38699 are notably different from the other spectra, specifically the decrease in slope in blue/green region followed by an increase >7000 Å.

When comparing telescope data with laboratory data, the orientation of the orbital debris surface is not known, and therefore, we have no knowledge of the angles of incidence and reflection. The only angle that we have knowledge of is the topocentric solar phase angle. Thus our interpretation of any comparison must be only first order. Other studies have used laboratory measurements to acquire bidirectional reflectance distribution function (BRDF) data to

measure reflectance data as a function of various incident angles and to compare with telescopic data [8,9]. The BRDF data for different materials will provide the baseline to identify material composition of satellite surfaces and orbital debris. Future OMC data will incorporate BRDF measurements to acquire varying incidence and reflectance angles for various shapes and materials that may help better interpret observational data.

In Fig. 7 laboratory spectral data are presented, normalized to the same 7500-8000 Å region as the telescopic data. The data shown are exposed white paint turned gold, exposed aluminum, black paint, white paint, iridited aluminum (which makes the aluminum appear gold), yellow paint, blue anodized aluminum, and Titanium (Ti6Al4V – one of the most common Titanium alloys). The exposed data was taken from the returned Long Duration Exposure Facility spacecraft. Color index data (e.g., B-V and B-R) cannot be extracted due to the limited range of spectral data acquired. The only filter that is totally encompassed by this range is V (~4500 - ~7000 Å). Therefore, the slope and overall characteristics of the spectra were analyzed. The slope of SSN 25000_May2012 and 25000_Jan2013 shows a factor of ~1.76 and ~1.55 in slope increase, respectively. The closest comparison to laboratory data is the white paint (shown in magenta in Fig. 7), which has an increase in slope of ~1.67. Considering the Titan Transtage presumably used white silicone paint on the forward heat shield, forward barrel section, pitch motor fairings, and a small percentage on the checkerboard pattern, it is highly probable that the surface property of SSN 25000 is white silicone paint.

In comparison, SSN 38690 presents the relatively flattest spectra, with a slope increase of ~1.14. Given the flat characteristics of Titanium, a known material used for the Titan Transtage fuel tanks, SSN 38690 was originally thought to best correlate with Ti6Al4V. SSN38690 has a slight dip in the visible regime, whereas Ti6Al4V is relatively flat throughout the same bandpass. Therefore, the SSN38690 best matches black paint, which has a slope increase of ~0.95. Based on the Titan Transtage schematic, black paint is not a given outer surface material, but it does not exclude black paint as an interior surface material on the Titan Transtage. A second conclusion would be this piece is composed of aluminum and covered with possible soot/fragmentation particulates as a result of the explosion, similar to the surface characteristics of the ESOC and SOCIT 'flake' laboratory samples as shown in Fig. 5. Both laboratory samples have B-R values close to 1, indicating the flux is equivalent in the blue and red region, similar to SSN 38690. If the Titan fragment is aluminum based, an absorption feature would be shown near ~8500 Å, but the slit is limited to 4500-8000 Å and thus not detectable with spectra. The last fragment presented, SSN 38699, does show an absorption feature centered near 7000 Å. Laboratory materials that have similar features include plastics and paints, such as the blue anodized aluminum shown in Fig. 7 [10]. The closest material approximation within the Titan Transtage Schematic is the pyrochrome paint coating (green) and moly-disilicide coating (blue) on the aft of the Transtage.

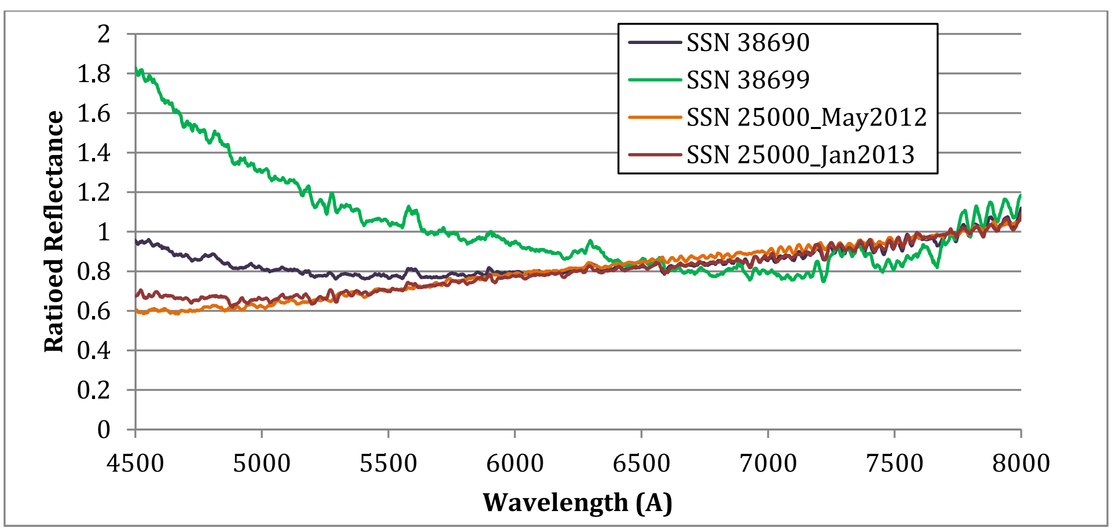

Fig. 6. SSN 25000 (May 2012 and January 2013), SSN 38690 and SSN 38699 spectra data normalized to 1 in the 7500-8000 Å region. The data has been smoothed using an 11 point moving average. Note: low frequency fringing seen near ~7750 Å is a defect of the detector and not of the data.

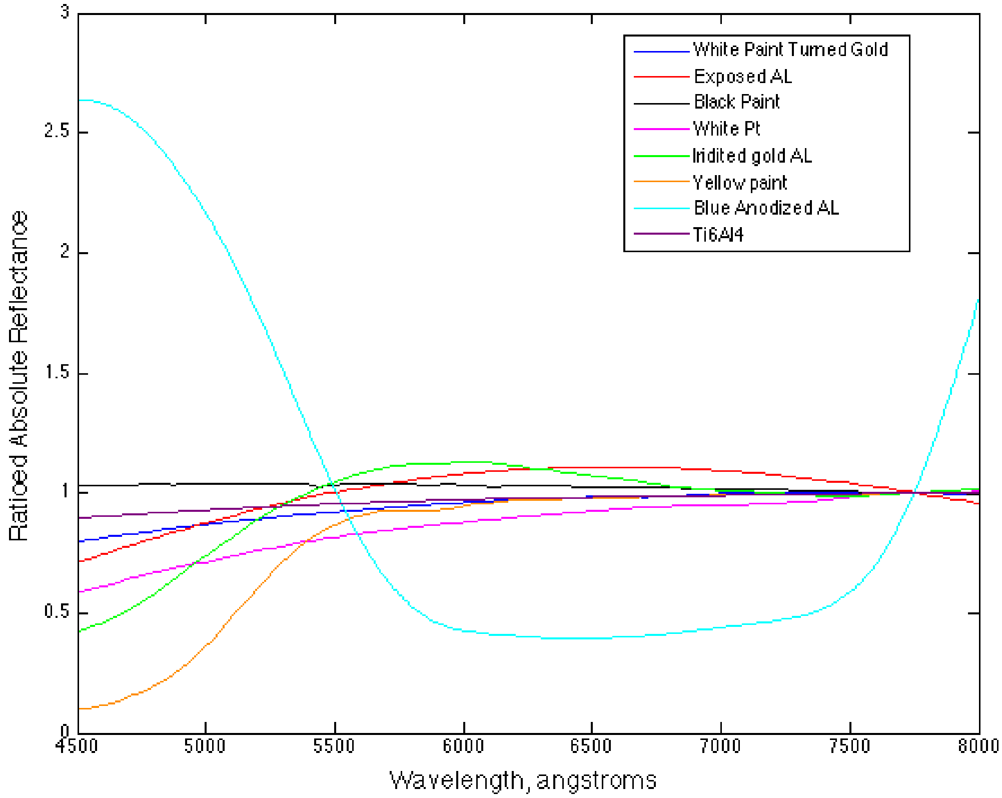

Fig. 7. Laboratory spectral data of spacecraft materials normalized to 1 between 7500-8000 Å.

3. Summary Table

The following table summarizes the Titan Transtage fragments material identification based on the photometry and spectroscopy data outlined in Section 2.2 and Section 2.3. The table identifies the SSN targets based on whether they were best matched to a metal, dielectric, or unknown. The majority of the observed titan fragments are correlated with dielectrics, such as composites and paints. The correlation to metal is likely aluminum, but more laboratory data is needed to determine if steel or titanium are probable material candidates.

Table 4. Titan Transtage Fragments and best correlated material association.

SSN	***Material***	***Likely Candidate Materials***
3432	Dielectric	composite
25000	Dielectric	white paint
25001	Dielectric	composite/electronic circuit board
33509	Metal	aluminum
33510	Metal	aluminum
38690	Dielectric/Metal	black paint/aluminum covered with particulates
38699	Dielectric	blue/green paint

4. Conclusions

Over a span of 5 years using standard survey data, several pieces associated with the Titan break-up were observed in broad R. The rocket body did prove to be the largest piece observed, as expected, and fragment SSN 25000 was determined to be the largest fragment in comparison to the other observed cataloged debris. LEGEND predictions show a moderate amount of fragmentation pieces linked with the original break-up categorized by size bins: >30 cm (observable with MODEST) and >10 cm. Although only 25 pieces have been cataloged by the SSN, there are a large number of potentially uncorrelated fragments that have orbital motions associated with the Titan break-up.

Photometric observations were also acquired on four different targets on separate dates with a range of phase angles. The data were compared with laboratory photometric results of common spacecraft materials from ground-based

impact tests, an explosion test, and various pristine samples. The Transtage (SSN 3432) B-R and B-V color indices best matched that of laboratory composite material, which is probable assuming the original Transtage is still relatively intact and we are observing various materials composed of white paint, metal, and other spacecraft components. The photometric results of SSN 25001 were in close proximity to the potted electronics and electronic circuit board. Based on known characteristics of aluminum and GFRP at various phase angles, the color index data of SSN 33509 linked best with aluminum. GFRP is translucent and the magnitude falls off more rapidly with increasing phase angles than aluminum. Also, GFRP is not a common spacecraft material for the Titan Transtage and its era of launch. SSN 33510 presented the largest spread in color data, and thus, surface material type could not be determined based on the laboratory samples presented. The closest laboratory materials to SSN 33510 were aluminum pieces from impact tests (flake) and explosion testing (ESOC) as the other nearby laboratory materials were not likely to be associated with this Transtage.

Spectral data on SSN 25000 over two observational periods were compared to laboratory spectra data of materials best thought to exhibit optical characteristics similar to what was once on the Titan Transtage. Aluminum and various paints were investigated, but it was the white paint that best matched in spectral shape and slope factor. Given the *a priori* information, a large portion of the Transtage was once covered with white silicone paint consistent with the material correlation analysis presented. The second Titan fragment studied was SSN 38690, which exhibited spectral characteristics close to black paint. Although black paint was not indicated as a surface material used in the Titan Transtage schematic, it does not exclude the possibility that it was used in the interior. SSN 38690 could also be an aluminum base covered in soot or fragmentation particulates resulting from the explosion, much like the impact test fragments and explosion fragments analyzed in the laboratory. The final Titan fragment analyzed was SSN 38699, which exhibited the bluest spectra characteristics and an absorption feature around 7000 Å, common with colored plastics and paints. This fragment is likely associated with pyrochrome paint coating (green) and moly-disilicide coating (blue) used on the main engine bells of the Transtage.

Future work will include a larger database of laboratory photometric and spectral data for comparisons, especially focusing on phase angle dependence on these materials. The goal of this research is to better understand materials associated with explosions to improve the risk-assessments for objects in orbit, better define density distributions, and provide insight into how the Titan Transtage may have fragmented. All of the information will be beneficial to providing a higher fidelity break-up model and environmental model of the GEO environment.

5. References

1. Barker, E., et al, “Comparison of Orbital Parameters for GEO Debris Predicted by LEGEND and Observed by MODEST: Can Sources of Orbital Debris be Identified?” *Proceedings of AMOS 2006 Technical Conference*, Maui, Hawaii, 2006.
2. Sousek, D., “Orbital Simulation of the Titan III Transtage Spacecraft” Proceedings of the IES, 1996, pp 561-576.
3. Barker, E., et al, “An Attempt to Observe Debris from the Breakup of a Titan 3C-4 Transtage,” *Proceedings of AMOS 2007 Technical Conference*, Maui, Hawaii, 2007.
4. Uetsuhara, M.,“Observation campaign dedicated to 1968-081E fragments identification,” *Advances in Space Research*, Volume 51, Issue 12, 15 June 2013, pp 2207–2215.
5. Mulrooney, M., Optical Phase Functions and Albedos of Orbiting Debris Objects, M.S. Thesis, Rice University, Houston, TX, April 1993.
6. Cowardin, H., “Characterization of Orbital Debris Photometric Properties Derived from Laboratory-Based Measurements, “*Proceedings of AMOS 2010 Technical Conference*, Maui, Hawaii, 2010.
7. Seitzer, P., et al, “Visible Light Spectroscopy of GEO Debris,” *Proceedings of AMOS 2012 Technical Conference*, Maui, Hawaii, 2012.
8. Bedard, D., “Measurement of the photometric and spectral BRDF of small Canadian satellites in a controlled environment,” *Proceedings of AMOS 2011 Technical Conference*, Maui, Hawaii, 2011.
9. Wellems, D. and Bowers, D., “Laboratory Imaging of Satellites and Orbital Appearance Estimation,” *Proceedings of AMOS 2007 Technical Conference*, Maui, Hawaii, 2007.
10. NASA Orbital Debris Spacecraft Materials Spectral Database.